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# Statistical multifragmentation features of midvelocity source in semiperipheral heavy-ion collisions


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Some characteristics of midvelocity emissions in semiperipheral heavy-ion collisions at Fermi energies are discussed in the framework of a multifragmenting scenario. We report on binary dissipative collisions of $^{93}$Nb + $^{93}$Nb at 38$A$ MeV in which we measured an abundant emission of particles and fragments not originated from the usual evaporative decay of hot primary fragments. We checked the compatibility of these emissions with the multifragmentation of a source which forms in the overlap region. One can fairly well reproduce the data assuming a hot and dilute source, possibly more n-rich than the initial nuclei; the results appear to be insensitive to the source size.



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## I. INTRODUCTION

The recent literature on experimental heavy-ions physics in (semi-) peripheral collisions at Fermi energies (see e.g. [1, 2, 3, 4, 5, 6, 7, 8]) often focuses on the emission of particles and fragments from the phase-space region in between the reacting nuclei, called midvelocity emission. This phenomenon has been already investigated by several authors, as a function of the size of the system and of the impact parameter, but its origin is far from being understood; in particular, it is not clear if one deals with only one hot source, if the source(s) is(are) locally thermalized and what are the regions accessed by these systems in the equation-of-state phase diagram. From a theoretical point of view, understanding the midvelocity emissions is linked to the more general issue of isospin dynamics [9, 10], which are supposed to be ruled by the symmetry-energy term. This term is unknown at the low barion densities predicted for the midvelocity matter when a neck develops between the interacting nuclei during the fast separation phase [7, 11].

Several experiments (e.g. [4, 6, 12]) have shown that the characteristics of the midvelocity emissions are very different with respect to the emissions from the quasi-projectile ($QP$) [and quasi-target ($QT$)] and standard evaporation codes can give a good reproduction of the $QP$ emissions, but not of the midvelocity emissions. From an accurate energy balance [3] it was found that the $QP$ and $QT$ become more and more excited with decreasing impact parameter. At the same time, already for peripheral impacts, the energy deposited in the matter emitted at midvelocity accounts for a large fraction of the energy globally dissipated into the internal degrees of freedom; it is possible that the resulting large excitations easily overcome the limit of 3-4$A$ MeV for which many authors have shown the onset of instabilities in nuclei. Therefore, we found appropriate to verify the compatibility of the experimental results with calculations performed in the frame of the Statistical Multifragmentation Model (SMM) [13, 14, 15].

## II. CHARACTERIZATION OF THE REACTION SCENARIO

The experimental data used for the comparison with the SMM calculations are those of the $^{93}$Nb + $^{93}$Nb collision at 38$A$ MeV [6]. The experimental setup, the analysis procedures and the method for separating the midvelocity emissions from the evaporative decays are described in detail in Refs. [6, 16]. Here we briefly remind that binary events were fully characterized by detecting in coincidence the $QP$ and the $QT$, together with the associated emissions of light charged particles (LCP, $Z \leq 2$) and intermediate mass fragments (IMF, $3 \leq Z \leq 7$); isotopic discrimination was obtained for Z=1 and charge identification for reaction products up to Z=7. Different aspects of the midvelocity emissions were presented elsewhere [1, 6, 17, 18] and their characteristics were compared with those of the sequential decay of the two main reaction products, the excited $QP$ and $QT$.

All the observables related to the hot $QP$ and $QT$ are compatible with the statistical decay of a source at normal density, which can reach excitation energies up to about 3$A$ MeV (T $\leq$ 6 MeV) [6, 17], in agreement with the findings of other authors [4, 12, 19, 20, 21] when comparable windows of impact parameter are selected. In particular, the LCP multiplicities and their ratios, as well as the neutron content of hydrogen isotopes (see for instance Figs. 10-12 of Ref. [6]), are in good agreement with the predictions of commonly used evaporation codes. (At variance with other authors, e.g. Ref.[22],

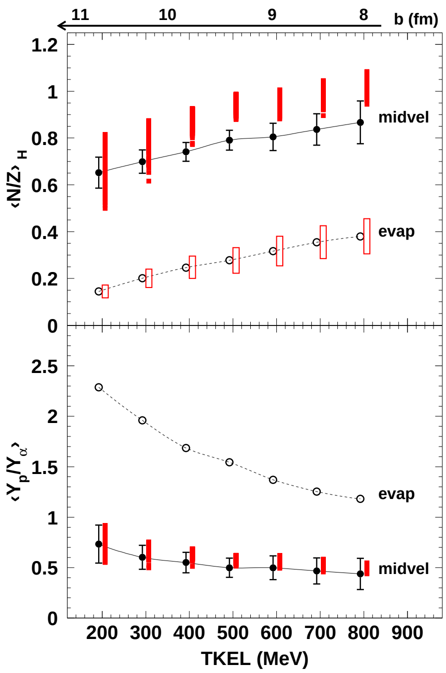


FIG. 1: (color online) Experimental observables for midvelocity (solid circles) and $QP$ (open circles) emissions as a function of TKEL: (a) Neutron to proton ratio for hydrogen isotopes; (b) Ratio of the yield of protons to $\alpha$-particles. The lines through the experimental points are guides to the eye. The vertical bars on the right of the experimental points correspond to the range of acceptable solutions of SMM calculations for the midvelocity source (solid bars) and the $QP$ (open bars), as explained in the text.

we don't need to invoke a statistical multifragmentation mechanism for the observed decay of $QP$ and $QT$).

On the contrary, the midvelocity emissions present features which make them strongly different from the usual decay of hot rotating nuclei. This is clearly shown by the results of Fig. 1. Part (a) of the figure presents the average experimental isospin-ratio of hydrogen, $\langle N/Z \rangle_H$, both for the midvelocity emissions (solid circles) and for the $QP$ decay (open circles), as taken from Fig. 12 of Ref. [6]. Part (b) of Fig. 1 presents the experimental ratio of the proton/$\alpha$-particle yields, $\langle Y_p/Y_\alpha \rangle$, again for the midvelocity emissions (solid circles) and for the $QP$ decay (open circles); this part has been derived from the multiplicities of Fig. 5 of the same Ref. [6].

The experimental results are presented as a function of a variable, TKEL, which is used here just as an "ordering parameter" to classify the events in bins of decreasing impact parameter [1]. This use of the variable TKEL has been extensively discussed in a previous paper [6], where it was shown that - even at Fermi energies - TKEL is strictly correlated with the relative velocity between $QP$ and $QT$ and, as such, it is an indicator of the violence of the collision (and hence of the impact parameter); this interpretation has been recently adopted also in a theoretical description of the reaction dynamics [11]. The estimated correspondence of TKEL with impact parameter for the data of this paper is displayed by the arrow at the top margin of Fig. 1. It shows that the presented data refer to semi-peripheral collisions in the impact-parameter range between 8 and 11 fm. More central events have not been used because, with decreasing relative velocity, the separation between midvelocity emissions and $QP$ (or $QT$) evaporation becomes more and more uncertain and hence the interpretation of the results would become less and less reliable.

From the data of Fig. 1 it is apparent that the midvelocity emissions present some substantially different characteristics with respect to the usual evaporative processes. While the $\langle N/Z \rangle_H$ ratio for particles emitted by the $QP$ (open circles) is rather low and it was found compatible with the results of GEMINI calculations for the decay of a $^{93}$Nb nucleus at normal density with the appropriate excitation energy [6], the same ratio for the midvelocity emissions (solid circles) is much higher and cannot be reproduced by usual statistical model calculations. Even more striking is the fact that the relative abundances of the emitted particles are different, displaying some remarkable inversions [6]; in particular Fig. 1(b) shows that the relative abundances of protons and $\alpha$ particles are reversed when going from the evaporative to the midvelocity emissions.

The exact nature of the midvelocity emissions is yet not fully ascertained. On the one hand, one observes a component which is evidently Coulomb-related [17, 20] to the main reaction products: this suggests that they are driven by the reaction dynamics towards rather elongated shapes, which quickly decay before complete decoupling from the formation stage [1, 20]. On the other hand, there are the very 'central' emissions, located at small velocities in the c.m. system: they may be attributed to the disassembly of the overlap region (possibly characterized by high excitations and small densities), or to the snap-off of distended neck-like structures formed just in between the two separating main products [4]. In any case, our previous results [3, 17] suggest that the energy density in this region may reach values well inside the region in which nuclear multifragmentation signals have been detected. Dynamical codes predict the formation of elongated structures in fast dissipative collisions in the Fermi energy domain [9, 11, 20, 23]. As to the timescale of the formation/emission processes, dynamical calculations [9, 11, 23] for semiperipheral reactions suggest that it should be short (about 100-200 fm/c), but still long enough to allow the system to reach at least a partial equilibration in some degrees-of-freedom at a freeze-out stage. The final conclusion about statistical equilibrium

[1] TKEL is defined as the difference between the initial center-of-mass energy $E_{\rm in}^{\rm c.m.}$ of the collision and the c.m. kinetic energy of the outgoing $QP$ and $QT$, assuming binary kinematics

can be obtained only with a comprehensive comparison with experiments.

Thus, an hypothetical "source" of the midvelocity emissions – supposing that it exists – may have a more complex configuration than that considered in the frame of a statistical multifragmentation model. Therefore, at variance with what one expects in central collisions, in peripheral collisions we are aware that SMM calculations may not reproduce all details of the midvelocity emissions, especially concerning the kinematical characteristics of fragments, where the role of dynamics is still quite important. Nevertheless, the chemical equilibrium, responsible for the isospin composition of the fragments produced in the source, may be established. If the model is able to capture – at least partly – some important characteristics of the process (which might be, e.g., the tendency of some portion of nuclear matter to rapidly decay after having reached a partial thermal and chemical equilibrium, or possibly some kind of dilution being subjected to mechanical strains), one may expect that the model displays reduced discrepancies with the experimental data than the usual low-energy statistical models. With this in mind, is seems appropriate to test the compatibility of statistical multifragmentation calculations with the measured properties of the midvelocity emissions.

## III. THE PARAMETERS OF THE SMM CALCULATIONS

The Statistical Multifragmentation Model (SMM) is a well developed code which describes the nuclear disassembly in various regimes [13, 14, 15]. Present SMM calculations include also the decay of the hot fragments produced at the freeze-out, via evaporation or Fermi break-up [13]. Therefore we can directly compare the "final state" quantities computed by the code with the experimental ones, which are by definition secondary, i.e. after sequential particle decay. For the comparison with the data, we consider here the two experimental variables, $\langle N/Z\rangle_H$ and $\langle Y_p/Y_\alpha\rangle$, already presented in the previous Section: being relative quantities, they are less sensitive to systematic uncertainties, both from the experimental and theoretical point of view. Other authors [2] used other experimental variables for a comparison with SMM.

In peripheral collisions the input values for the SMM calculations are by far less obvious than in the usual applications of the model, which mostly refer to a single source produced in central collisions [21, 24]. There are no reliable hints concerning the appropriate values for the source size $A_s$, its charge $Z_s$ and its excitation energy per nucleon $\epsilon_s$, as well as their dependence on impact parameter. In fact, besides the uncertainties due to the usual lack of information about the emitted free neutrons, in peripheral collisions the process may be more complicated than the simple emission from a source: for example, part of the ejected matter could be reabsorbed by the $QP$ and $QT$ which, while flying apart, are still rather close to each other during the midvelocity emission phase [17].

Given these uncertainties on the source parameters, we decided to run many SMM calculations with a wide grid of input values for $A_s$, $Z_s$ and $\epsilon_s$. A lower limit for the charge of the source, $Z_s$, was given by the experimental total charge of the midvelocity emissions, $\langle Z_{midv}\rangle$, which smoothly increases with TKEL, up to about 12–15 for the highest TKEL values considered in this paper. In other words, the lower limit for $Z_s$ corresponds to the extreme assumption that the source completely disassembles into the measured total charge $\langle Z_{midv}\rangle$. As an upper limit, one might have taken the overlap matter in a participant-spectator picture (with or without taking into account the diffuseness); however, in order not to bias the results with a too restricted choice, we preferred to use in all cases a value of 50 charge units, which is rather large (it corresponds to more than half of the total charge of our system and we recall that we are dealing with peripheral collisions), checking afterwards the sensitivity of the results on this parameter.

The second input parameter is the mass of the source, $A_s$. Multifragmentation processes are much more sensitive to the neutron content of the source, $(N/Z)_s \equiv (A_s - Z_s)/Z_s$, than to the source size itself. In fact the isospin dynamics are supposed to play a relevant role in the fragment production, either via the density dependence of the symmetry energy [9, 23] or via polarization effects of the nuclear matter due to the Coulomb field [19, 25]. Our symmetric system has an initial N/Z value of 1.27, but we have no other clue on the isospin evolution during the interaction and hence on the N/Z values appropriate for the various portions of the system. If no free midvelocity neutrons were emitted at all, from the experimental data one would obtain for the midvelocity emissions a low (maybe unrealistic) value of N/Z=1.02-1.06 at $TKEL \geq$400MeV. Therefore, again in order not to bias the results, for each $Z_s$ we allowed a large variation of the source size $A_s$, so that the resulting ratio $(N/Z)_s$ was comprised in the wide range between 0.9 and 2.0.

Concerning the excitation of the source, $\epsilon_s$, the experimental value obtained via calorimetry – assuming a complete disassembly of the midvelocity source into midvelocity emissions, plus some neutrons (Fig.3 in Ref. [3] or Fig.9 in Ref. [6]) – points to high excitations for the overlapping matter, well above the values deduced for the $QP$ and $QT$. In the calculations we let $\epsilon_s$ span the range from 4 up to 9 MeV, which approximately corresponds to the vaporization limit. We neglect any radial-energy contribution to the excitation, as it has been shown that the compression-expansion cycle is weak in peripheral reactions [21]. Moreover SMM results on fragment yields are insensitive to radial flow [2].

Another parameter of SMM calculations is the freeze-out density of the source. Values of $\rho$ ranging from $\rho_0/6$ [2] to $\rho_0/3$ [22, 24, 26, 27] have been commonly used in

SMM calculations (with $\rho_0$ normal nuclear density). The possibility that dilute systems are formed also in semiperipheral collisions has been suggested by BNV calculations [9] which show that, for a system of similar size ($^{124}$Sn + $^{58}$Ni at 35$A$ MeV (b=6 fm)), very low densities can be attained in the neck region within 160-250 fm/c, especially when a soft equation-of-state is assumed. We run SMM with the value $\rho = \rho_0/6$ and we verified that the results do not appreciably change when increasing the density up to $\rho = \rho_0/3$.

A last word on the source shape: the inclusion of deformed shapes for the source modelization is in principle relevant. As already said, elongated transient nuclear systems are likely to be formed in semiperipheral collisions; recently, exotic shapes have been suggested even for central event sources, thus leading to multifragment calculations for non-spherical configurations [28]. However we think that our data concerning isotopic yields of lightest fragments are insufficient to investigate with SMM also this degree-of-freedom, which therefore has been neglected here (only spherical geometry is assumed).

## IV. COMPARISON WITH THE DATA AND DISCUSSION

Among the many triples $(A_s, Z_s, \epsilon_s)$ defining the sources on the grid for the SMM calculations, we retained only those for which both calculated values of $\langle N/Z \rangle_H$ and $\langle Y_p/Y_\alpha \rangle$ differed from the corresponding experimental values by less than 25%. Out of over 5000 triples used for the input grid, only about 200 were found to pass the above mentioned criterion of goodness at each TKEL. The values of $\langle N/Z \rangle_H$ and $\langle Y_p/Y_\alpha \rangle$ for the so defined "good" SMM sources are shown, for each TKEL, by squares in Fig. 1. Since all the "good" sources tend to give values of these two parameters quite close to each other, the squares tend to bunch up into the vertical solid bars which are visible in Fig. 1, slightly shifted -for the sake of clarity- to the right of each experimental point.

It is worth noting that many slightly different sources, all with rather reasonable parameters, are able to simultaneously reproduce both experimental correlations of Fig. 1, including their dependence on impact parameter; this is a result which was **not** obvious *a priori*.

As it was already shown in Ref. [6], the midvelocity emissions are appreciably richer in deuterons and tritons (with respect to the protons) than the evaporative emissions, a feature which is reproduced by the SMM calculations. The results of the SMM calculations tend to be even more n-rich than the experimental data, but the discrepancy is not very large [2]. Also the inversion in the relative abundances of protons and $\alpha$-particles between midvelocity and evaporative data, which is displayed by the ratio $\langle Y_p/Y_\alpha \rangle$ in Fig. 1(a), is well reproduced by the same "good" SMM calculations.

This comparison shows that the examined features of midvelocity emissions bear a closer resemblance with the expectations of a multifragmentation model than with those of a sequential decay. To give more support to this last statement, we note that, in its recent versions, the SMM code has been upgraded to treat also the 'standard' evaporation of hot nuclei at moderate excitations and normal density. Therefore we have run the SMM code also in this mode (with input parameters similar to those used for previous GEMINI calculations, see Fig. 12 of Ref. [6]) and also this comparison with the experimental data for the $QP$ decay is presented by the open bars to the right of the open circles in Fig. 1(a). It is worth noting that the large difference in $\langle N/Z \rangle_H$ between evaporative and midvelocity emissions is well reproduced by SMM. We did not try to calculate $\langle Y_p/Y_\alpha \rangle$ for the evaporation of the $QP$ within SMM, since this ratio strongly depends on the angular momentum of the emitting source [30, 31]. This would require the determination of angular momentum as a function of the impact parameter for the $QP$ source and it would divert from the main subject of the paper, which concerns the midvelocity source.

It may be worth examining in more detail the parameters of the "good" sources which lead to the observed agreement with the experimental points for the midvelocity emissions (circles in Fig. 1). For the source size $A_s$, rather flat distributions are obtained, thus indicating the insensitivity of the presently considered isospin quantities to this SMM parameter; a similar insensitivity of other experimental quantities to the source size was already noted in Refs. [2, 4]. Concerning the energy density, $\epsilon_s$, in all cases the best agreement is obtained for rather large excitation energies, well inside the multifragmentation region: most good triples have $\epsilon_s$ in the range 7–9 MeV, with a very weak tendency to increase with increasing TKEL.

Coming to the neutron content, the $(N/Z)_s$ of the "good" sources is presented as a function of $TKEL$ in Fig. 2, where all distributions have been normalized to unity. It is interesting to note that the average value of $(N/Z)_s$ (indicated by the arrows in Fig. 2) displays a definite increasing trend with increasing TKEL. Only in the most peripheral bin it remains below that of the colliding system (1.268, indicated in figure by the vertical line), while for the other less peripheral bins it rises and reaches values around and above 1.4. If the source size increases with decreasing impact parameter, this might naturally tend to privilege higher $N/Z$ values. To ex-

[2] We note that the midvelocity yields, obtained in [6] by subtracting the evaporative component from the total, actually refer to all not-equilibrated emissions, including those which are anisotropically distributed on the Coulomb ridges of the $QP$ and $QT$ [17, 29] and might be less exotic in their neutron content.

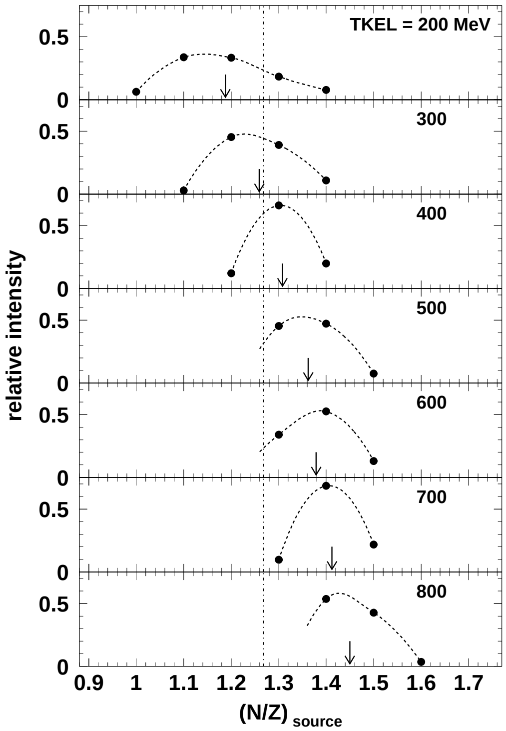


FIG. 2: $(N/Z)_s$ distributions for the midvelocity multifragmenting sources of the SMM calculations which produce the results shown in Fig. 1. From top to bottom, the TKEL windows go from very peripheral to mid-peripheral events. Each distribution is normalized to unit area and the arrow shows its average value; the vertical line is the $N/Z$ of the system.

clude this trivial explanation, we checked that no appreciable correlation exists between $(N/Z)_s$ and $A_s$; in addition, limiting the accepted source sizes to 40 amu does not change the trend observed in Fig. 2. One could have attributed this trend to the required agreement with $\langle N/Z\rangle_H$, an experimental observable which strongly depends on deuterons: because of their more diffuse wave function, deuteron production could be enhanced in too diluted configurations [2]. However, it was verified that increasing the freeze-out density to $\rho = \rho_0/3$ produces negligible effects on the behaviour of $(N/Z)_s$.

The question of a possible neutron enrichment is widely discussed in the literature. Theoretically, Landau-Vlasov calculations with different chemical potentials for neutrons and protons predict -for the neck matter- a neutron enrichment with respect to the initial value when an asy-stiff equation-of-state is used [9, 11, 23]. For example, in a recent work [11], several effects contributing to isospin dynamics in semiperipheral reactions were studied. The predicted n-enrichment of the neck-matter occurs, even for symmetric systems, via the socalled "isospin migration" process, which sets in because of the density gradient between the $QP$ (and $QT$) and the more diluted neck matter. The observed rising trend of $(N/Z)_s$ with increasing centrality is in agreement with other experimental indications [12]. The rather peripheral impact parameters addressed in this work ($b \approx$ 8–11 fm) do not allow to check whether the N/Z of the midvelocity matter decreases for substantially more central collisions, as it is predicted by some dynamical calculations (see, e.g., [32]).

Experimental results are not easy to compare with each other and they usually give indications based on the isotopic analysis of only some species (IMFs or LCPs) emitted by the multifragmentation of the source. These partial results are usually interpreted as indications that, already in peripheral collisions, the midvelocity source is neutron enriched with respect to the the $QP$ source (see e.g. [2, 4, 8, 22]). Complete measurements of all kinds of products emitted at midvelocity are rare. Combining the data of two experiments, one about the free neutrons and the other about the charged products, it was concluded [33] that globally all the material found in the midvelocity region is likely to have the same N/Z ratio as the bulk matter. However, more recently, a simultaneous isotopic analysis of all emitted products (IMFs, LCPs and neutrons) has been performed [12], leading to the opposite conclusion: although the errors are very large, it gives support to the idea that the midvelocity matter is more n-rich than the initial system and it tends to become even more n-rich with decreasing impact parameter.

In the present case, the results of Fig. 2 are just a model-dependent indication that some of the features observed at midvelocity point to a possible neutron enrichment of the neck region, once a statistical multifragmentation mechanism is assumed to be responsible for this kind of emissions. Whether this possible neutron enrichment is mainly produced by density dependent effect[9, 10, 11], or by a lowering of the symmetry energy in the dilute hot multifragmenting systems[34], or by some other exotic mechanism, is still an open and widely debated question, which deserves further investigation.

## V. CONCLUSIONS

In semiperipheral collisions ($b \geq$8 fm) at Fermi energies it was found that the experimentally observed intense emission of reaction products from the midvelocity region displays some characteristics which are quite different from those of the usual evaporation from hot nuclei. The excitation energy per nucleon in the overlap region has been estimated to be well above the commonly accepted limit for multifragmentation. Therefore, we have investigated in how far the behavior of the above mentioned experimental quantities may be reproduced by calculations in the frame of the Statistical Multifragmentation Model (SMM). The main outcome of this investigation is that it is indeed possible to find source parameters such that the final multifragmentation products reproduce reasonably well the observed peculiar features of

midvelocity emissions. In particular they reproduce the neutron enrichment of the emitted hydrogen isotopes, as well as the inversion of relative abundances of protons and $\alpha$-particles with respect to an evaporative process. These SMM sources, while showing no preference for a particular size $A_s$, are characterized by rather high excitation energies (7–8 MeV per nucleon) and by a tendency to become more neutron-rich than the colliding system with decreasing impact parameter.

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